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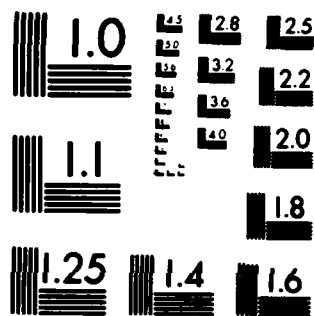
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## EFFECTS OF ION-ACOUSTIC INSTABILITY ON LIGHT ION BEAM TRANSPORT IN DEUTERIUM CHANNELS

### I. Introduction

In a previous work<sup>1</sup>, the magnetohydrodynamic response of plasma channels to propagating ion beams has been investigated. It was found that 3 MeV, 0.5 MA, 50 nsec proton beams could be transported in one cm<sup>2</sup> deuterium plasma channels without major disruptions of the channel. This conclusion was further supported by the results of a review on instabilities of ion beam propagating in preformed channels<sup>2</sup>. However, when the primary ion beam current is increased to several MA, Fig. 3 in ref. 1 for example shows that large values of  $T_e/T_i$  can be reached in the channel (of order 10) favoring the growth of ion-acoustic instabilities and that unfavorable structure in the radial B field profile may appear, raising questions about the confinement of injected ions in the channel. In both of these cases, classical transport which was assumed previously is not a good assumption.

In this work, we modify the transport coefficients due to the onset of ion acoustic instabilities, we determine the conditions under which ion acoustic instabilities are most likely to occur and recalculate the channel response when the effects of these instabilities are included. Changes in channel resistivity modify axial energy losses of the beam during propagation and consequently the optimum channel density for minimizing these energy losses<sup>3</sup>. In a first section, we look at the ion-acoustic instability and its consequences on the physics of the problem. Then in a second section, we present the results of this study and we draw conclusions. It appears as though ion-acoustic instability and the associated anomalous beam slowing down are not very important effects on the ion beam propagation in the plasma channel.

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## II. Ion-acoustic Instability

We have already described the treatment of ion-acoustic instabilities in fluid calculations<sup>4</sup>. For sake of completion, we outline this treatment here, but the emphasis will be on the differences between the present case and the previous one. In the present case, a return current flows through the channel, heating up the electrons. If we denote the current drift velocity by  $V_D$ , the ion-acoustic instability is excited when

$$V_D > V_s \left[ 1 + Z \sqrt{\frac{M}{m}} \left( \frac{T_e}{T_i} \right)^{3/2} \exp \left( - \frac{V_s^2 M}{2T_i} \right) \right] \quad (1)$$

where  $V_s$  is the ion sound speed given by

$$V_s = \frac{\omega_{pi} \lambda_{De}}{\sqrt{2}} \left[ 1 + 12 \left( \frac{T_i}{T_e} \right) \right]^{1/2} \quad (2)$$

All the symbols are standard ( $M$  is the ion mass,  $m$  is the electron mass for instance) and the temperature is expressed in ergs. The expression for the instability threshold is valid when  $ZT_e \gg T_i$ . When the Debye length  $\lambda_{De}$  is substituted by its expression as a function of density and electron temperature, Eq. (1) can be expressed as a condition for  $V_D/V_e$  where  $V_e$  is the electron thermal velocity. For a deuterium plasma ( $Z = 1$ ,  $M/m = 3700$ ),  $V_D/V_e$  has a maximum around  $T_i/T_e = 0.45$ . For larger values of  $T_i/T_e$  - this situation occurs in the channel at its edge because of shock heating - we use the following expression which is the approximate condition for the two-stream instability

$$V_D/V_e = 0.84 \frac{T_i}{T_e} + 0.2. \quad (3)$$

A smooth transition between the regimes defined by relation (1) and (3) is assumed and has been implemented into the code.

Once the threshold conditions have been met the effects of ion-acoustic instabilities on the plasma behavior take place. These effects have been discussed in ref. 4 and arise from an anomalous collision frequency, anomalous electron-ion energy exchange and increased electric field which generates the return current. Of particular importance to the present work is the enhanced electric field which decelerates the beam ions in the channel and thus

increases their slowing down. This electric field is simply calculated as  $\eta_{an} j$  where the anomalous collision frequency has been chosen

$$\nu_{an} = 10^{-3} \omega_{pe}. \quad (4)$$

A factor of  $10^{-2}$  instead of  $10^{-3}$  was also tried in the computation, but the difference was not significant. Anomalous heat transport was not included.



### III. Results

In this section, we first look at the physical regime for which the ion-acoustic instability is important. From the results of ref. 1, we have already seen that the temperature ratio  $T_i/T_e$  in the channel at the end of the beam pulse varies between 0.7 for a 400 kA proton beam and 0.1 - 0.2 for the 2 MA case. From the threshold condition, we know that the instability will occur when  $V_D/V_e$  lies around 0.8 - 0.4 for the temperature ratios just quoted. Taking the larger value, expressing  $V_e$  as a function of  $T_e$  and using the relation between the temperature and current density found in ref. 1, we find that the equivalent threshold condition which must be satisfied by the current density for the instability to take place is

$$j_b > 5 \cdot 10^{-29} \frac{n_e^2}{\epsilon} \quad (5)$$

where  $j_b$  is in A/cm<sup>2</sup>,  $n_e$  in cm<sup>-3</sup> and  $\epsilon$  the ion beam energy in MeV. This expression is valid for a proton beam in a deuterium background channel for a 50 nsec ion beam pulse. In the bunched stage, we know that  $j_b t$  is constant and condition (5) becomes more easily satisfied, especially when the numerical factor on the right hand side drops to 1 for a 10 nsec pulse. For  $n_e = 10^{18}$  cm<sup>-3</sup>,  $\epsilon = 1$

$$j_b > 10^7 \text{ A/cm}^2$$

in the bunched stage. Another factor which helps in meeting that criterion is the reduced channel density after the beam has been injected. This reduction factor has been estimated in ref. 3 and should also be taken into account.

We now present results for a bunched case,  $j_b = 10^7$  A/cm<sup>2</sup>,  $n_0 = 4 \cdot 10^{17}$  cm<sup>-3</sup> and  $\epsilon = 2$  MeV. Profiles for density and temperature as a function of channel radius with and without the instability are shown near the end of the pulse at  $t = 8.2$  nsec in Figs. 1 and 2. For the anomalous transport case, heating is higher at the channel-gas blanket interface. Also, because of the larger current resulting from the anomalous resistivity, the B-field has more structure than in the classical case.

As mentioned before, one of the most important quantities which comes out

of this study is the decelerating axial electric field in the channel. The slowing-down of the injected beam is expected to be larger in the unstable case because of the anomalous resistivity. The electric field shown in Fig. 3 has been averaged over radius according to the expression

$$\langle E \rangle = \frac{\int E_z(r) 2\pi r dr}{\pi r_{ch}^2}$$

and includes also the collisional slowing-down of the beam in the channel. It is shown as a function of initial channel density for the same conditions as indicated before at  $t = 8.2$  nsec, i.e., just before the end of the beam pulse. From this figure, we see that the average electric field for the unstable case is larger than for the classical one but not by a large amount. The difference goes from about one percent at  $n_1 \sim 10^{18} \text{ cm}^{-3}$  to 45% at  $n_1 = 2.5 \cdot 10^{17} \text{ cm}^{-3}$ . The field reaches a minimum as found in ref. 3 when energy losses due to motion of the channel ( $V \times B$  term in the electric field inversely proportional to density) equal losses due to beam deposition (proportional to density). The density value at which this minimum occurs can be compared with the simple estimates given in ref. 3. For the present parameters, these estimates give the minimum in energy losses for  $n_1 = 1.8 \cdot 10^{18} \text{ cm}^{-3}$  whereas the numerical results in Fig. 3 show it at  $10^{18} \text{ cm}^{-3}$ . For the most efficient transport, channels should operate on the high-density side of the minimum (since the losses do not go up as fast with a variation in density than on the other side). It is also the side where effects of ion-acoustic instability are smaller. For this reason, it does not seem that anomalous transport plays an important role in beam transport studies.

In summary, we have looked at the effects of ion-acoustic instability on channel transport. Anomalous transport coefficients have been included in a one-dimensional radial mhd code. The effects of anomalous transport have been shown to be significant only in the bunched stage when the initial channel density is below its optimum value. Because of these characteristics, it is our conclusion that effects of ion-acoustic instability do not seem to be important for beam transport studies.

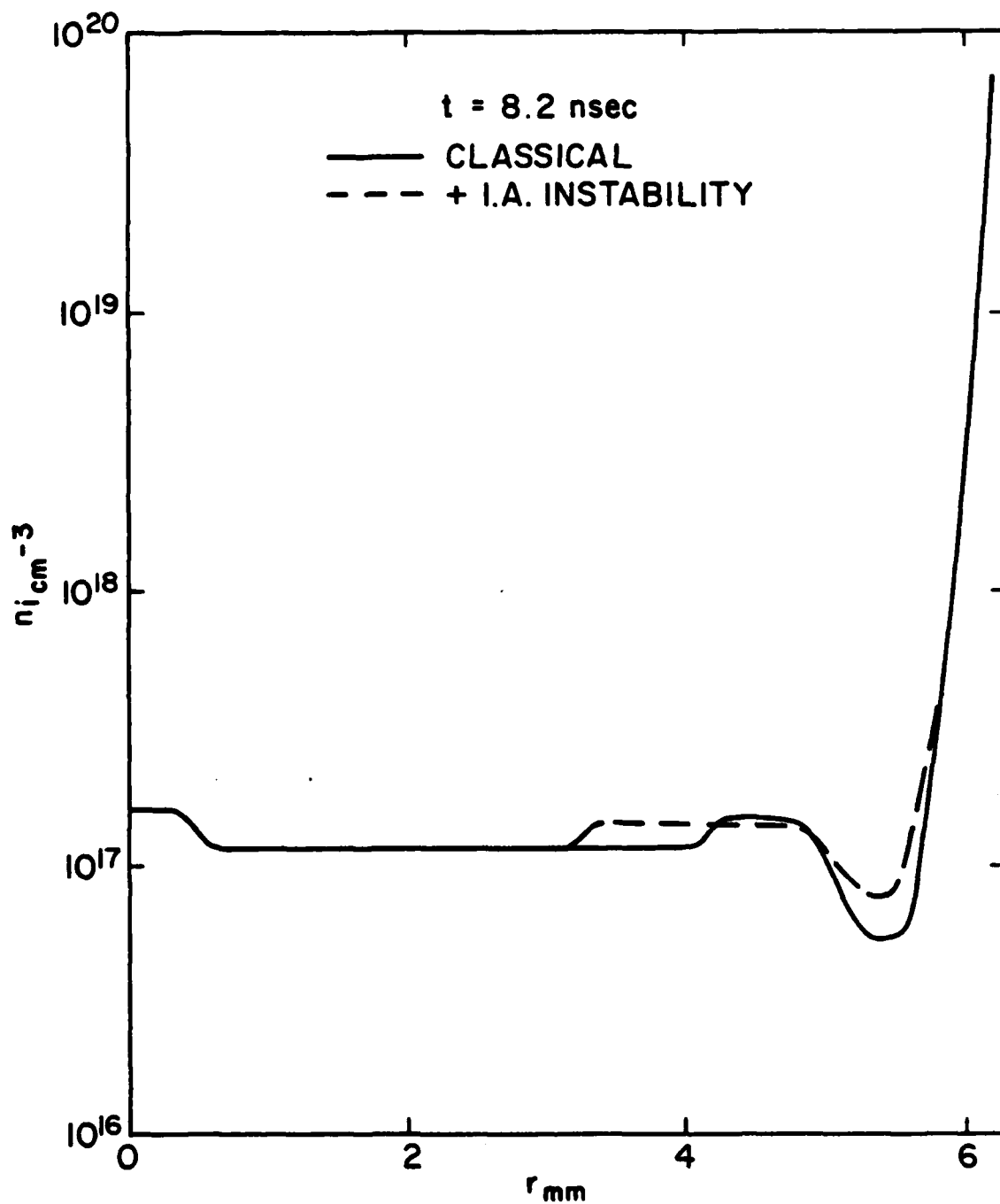


Fig. 1. Plasma channel density profiles with and without ion-acoustic instability for  $j_b = 10^7 \text{ A/cm}^2$ ,  $n_0 = 4 \times 10^{17} \text{ cm}^{-3}$  and  $\epsilon_b = 2 \text{ MeV}$  at  $t = 8.2 \text{ nsec}$ .

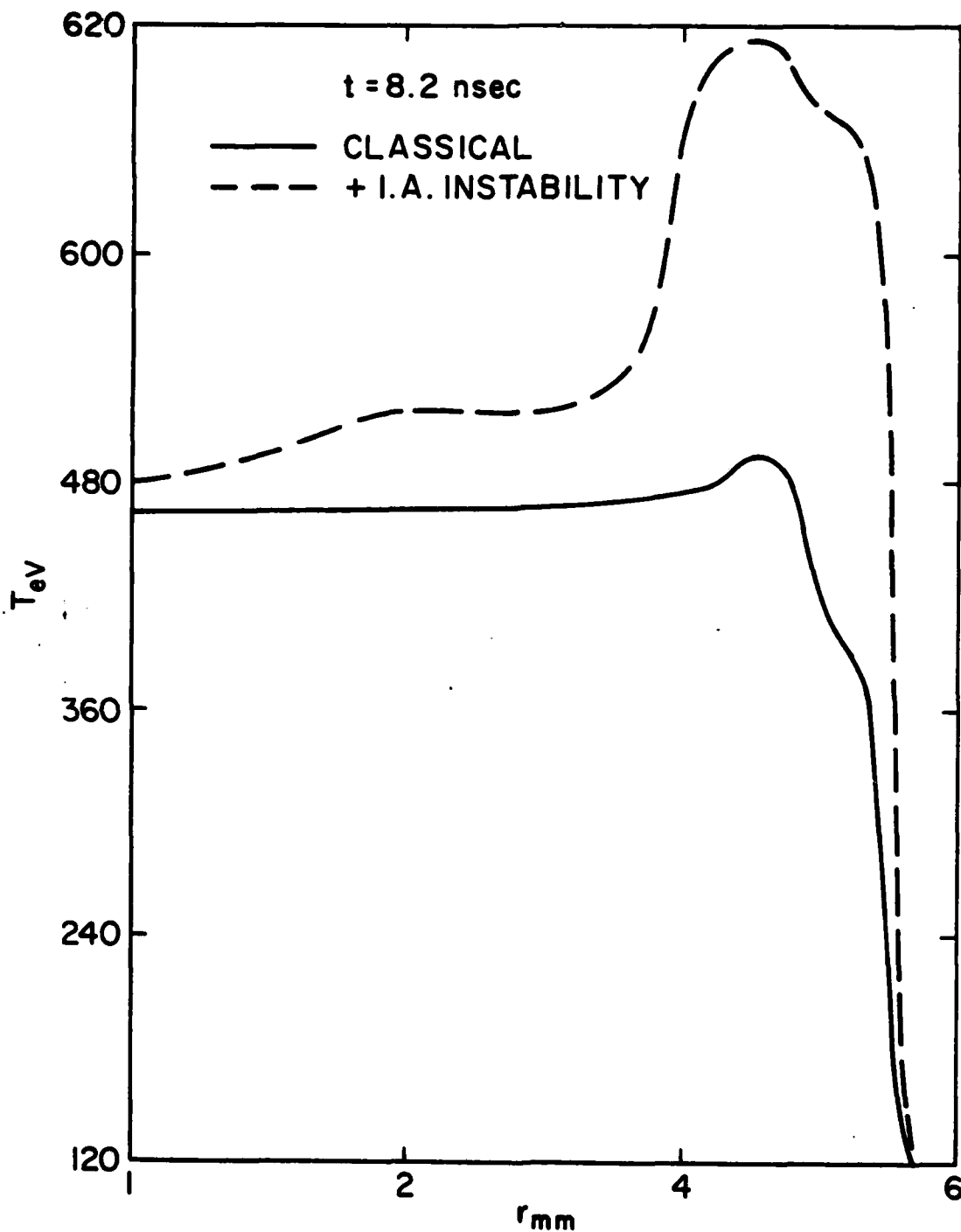


Fig. 2. Plasma channel temperature profiles with and without ion-acoustic instability for same parameters as Fig. 1.

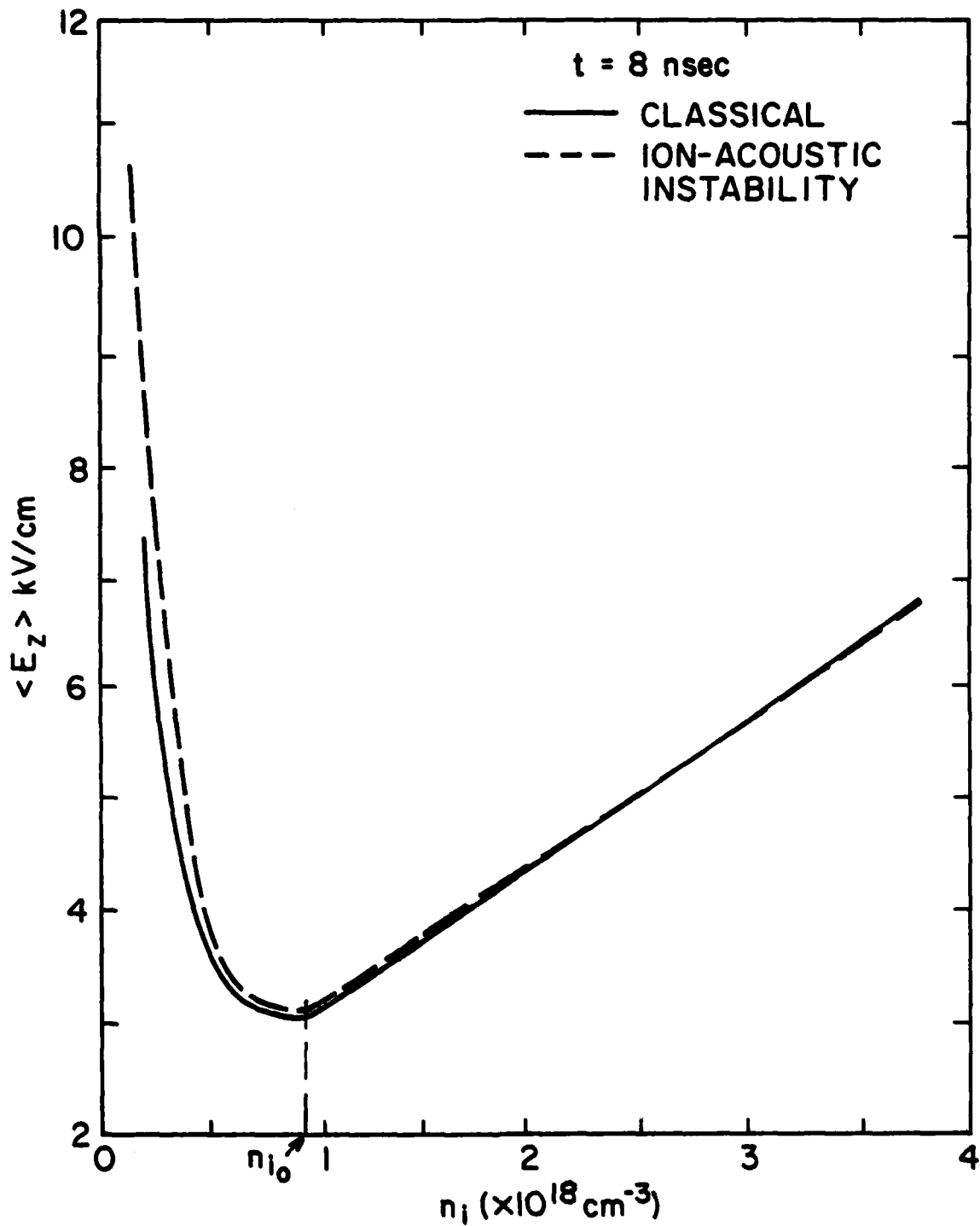


Fig. 3. Equivalent axial electric field with and without ion-acoustic instability as a function of initial channel density at  $t = 8 \text{ nsec}$  for  $j_b = 10^7 \text{ A/cm}^2$  and  $\epsilon_b = 2 \text{ MeV}$ .

### Acknowledgments

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